

ESTCP Cost and Performance Report

(WP-200303)



Scale-Up, Demonstration and Validation of Environmentally Advantaged and Reliable Coatings: FP 60-2 Experimental Coating

July 2008

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ENVIRONMENTAL SECURITY
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COST & PERFORMANCE REPORT

Project: WP-0303

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ACRONYMS AND ABBREVIATIONS

AFP	Air Force Plant
AFP 4	Operated for the U.S. Government by LM Aero at Ft. Worth, TX
AFP 42	Operated for the U.S. Government by LM Aero, Northrop Grumman, Boeing, and others at Palmdale, CA
AFRL/MLSC	Air Force Research Laboratory, Materials and Manufacturing Directorate, Acquisition Systems Support Branch
AMS	SAE Aerospace Material Specification
ASC/ENVV	Aeronautical Systems Center, Acquisition Environmental, Safety & Health Division, Pollution Prevention Branch
ASTM	American Society for Testing and Materials
BACT	Best Available Control Technology
CAA	Clean Air Act
CI	Confidence Interval
DoD	Department of Defense
ECAM	Environmental Cost Analysis Methodology
EPA	Environmental Protection Agency
ESTCP	Environmental Security Technology Certification Program
FED-STD	Federal Standard
FP 212	Low VOC, rapid deposition, quick cure coating demonstrated/validated for ASC/ ENVV and ESTCP
FP 60	Baseline coating
FP 60-2	Low VOC, rapid deposition, quick cure coating demonstrated/validated for ASC/ ENVV and ESTCP
g/L	Grams per Liter
GOCO	Government-Owned, Contractor-Operated
HAP	Hazardous Air Pollutant
IRR	Internal Rate of Return
LCC	Life-Cycle Cost
LM Aero	Lockheed Martin Aeronautics Company
MEK	Methyl Ethyl Ketone
MIBK	Methyl Isobutyl Ketone
MPK	Methyl Propyl Ketone
Mil	0.001 inches

NAVAIR	Naval Air Systems Command
NDCEE	National Defense Center for Environmental Excellence
NESHAP	National Emission Standards for Hazardous Air Pollutants
NPV	Net Present Value
Northrop	Northrop Grumman Corporation
O&M	Operations and Maintenance
OEM	Original Equipment Manufacturer
OMB	Office of Management and Budget
PDM	Programmed Depot Maintenance
PPE	Personal Protective Equipment
QPL	Qualified Products List
RH	Relative Humidity
RT	Room Temperature
SAE	Society of Automotive Engineers
SAIC	Science Applications International Corporation
SPO	Systems Program Office
TIM	Technical Interchange Meeting
UV	Ultra Violet
VOC	Volatile Organic Compound
WPAFB	Wright-Patterson Air Force Base
WS	Weapon System

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EXECUTIVE SUMMARY

SCOPE OF ESTCP PROJECT WP-0303

The overall scope of this ESTCP Project (WP-0303) focused on testing and demonstrating two low Volatile Organic Compound (VOC), rapid deposition, quick cure aerospace coatings. These coatings, FP 60-2 and FP 212, were formulated to meet the material property requirements of separate Weapon Systems (WS). At the start of this ESTCP program, FP 60-2 and FP 212 were in different stages of development and use and had different qualification and demonstration requirements for the two WS platforms of interest, which necessitated two separate ESTCP Demonstrations Plans, one for FP 60-2 and one for FP 212. Separate ESTCP Cost and Performance Reports were written to report on the results of completing the two Demonstration Plans. This report addresses the Cost and Performance of FP 60-2, with periodic references to FP 212 test results that provided risk reduction for FP 60-2 testing and demonstration. The ESTCP Cost and Performance Report for FP 212 is available from ESTCP.

BACKGROUND

Conventional aerospace coatings are typically applied as paints to varying thicknesses, depending on the specific application. Applying these coatings to desired thicknesses often requires significant labor hours for application, requiring multiple application passes of only a few mils (mil = 0.001 inch) per pass while allowing 5 to 10 minutes between passes for solvent flash. Typical aerospace coating stack-up applications require several hours and multiple working shifts to complete, as well as long cure times which often create bottlenecks in Department of Defense (DoD) production and Programmed Depot Maintenance (PDM) processes and result in logistical issues during field repairs. These coatings often contain significant quantities of VOCs and Hazardous Air Pollutants (HAPs) such as Methyl Ethyl Ketone (MEK), Methyl Isobutyl Ketone (MIBK), toluene, or xylene. The continued use of these high-VOC/HAP processes presents significant logistical and safety issues, as well as relatively long manufacturing/repair flow times. Use of low VOC, rapid deposition, quick cure aerospace coatings has the potential beneficial impacts of improving worker safety, reducing VOC/HAP emissions, and decreasing the flow times of manufacturing and repair processes.

This program demonstrated the performance of a low VOC, rapid deposition, quick cure aerospace coating, designated FP 60-2. The VOC content of FP 60-2 is 213 g/L, which is a 51 percent reduction in VOC content relative to the baseline coating, FP 60, with a VOC content of 432 g/L. The relatively low VOC content of FP 60-2 was achieved by using acetone as the primary solvent. According to Environmental Protection Agency (EPA) guidelines, acetone is not considered a VOC since it does not react with atmospheric compounds to form ozone in the lower atmosphere. Acetone was also the main driver for the rapid deposition, quick curing nature of FP 60-2. The vapor pressure of acetone is relatively high (180 mmHg at 20°C), which allows much of it to evaporate prior to reaching the substrate when FP 60-2 is being applied, resulting in relatively high effective build rates (mils/pass) and quick cure times.

Lab-scale studies were performed on FP 60-2 to assess physical, mechanical, and application properties. These lab-scale tests provided the data required for qualification of FP 60-2 to the relevant material specifications. The full-scale capabilities of FP 60-2 were demonstrated and validated during full-scale application studies.

OBJECTIVES OF THE DEMONSTRATION

The objectives of this demonstration were to qualify FP 60-2 per the relevant material specification and to demonstrate environmental and economic advantages of FP 60-2 relative to the baseline coating, FP 60. Lab-scale testing was carried out by Lockheed Martin Aeronautics Company (LM Aero) at Air Force Plant 4 (AFP 4), Ft. Worth, TX and by Northrop Grumman Corporation (Northrop) in El Segundo, CA. FP 60-2 completed all lab-scale testing as required by the relevant material specification. The results from this testing led LM Aero and Systems Program Office (SPO) personnel to conclude that FP 60-2 had passed all qualification testing per the relevant material specification. Full-scale application studies performed at AFP 4 using full-scale manual spray equipment and a full-scale engineering prototype provided side-by-side comparisons of the application properties of FP 60-2 and FP 60 and confirmed environmental and economic advantages of FP 60-2 relative to FP 60.

REGULATORY DRIVERS

Title V of the Clean Air Act (CAA) was the primary regulatory driver for this project. Aerospace coating stack-ups often contribute significantly to a facility's overall emissions, which are subject to state, local and site restrictions on total VOC emissions and are regulated under the National Emission Standards for Hazardous Air Pollutants (NESHAP) regulations.

DEMONSTRATION RESULTS

All critical FP 60-2 performance testing requirements were achieved during this program, which will allow FP 60-2 to be listed on the relevant LM Aero and Northrop Qualified Products Lists (QPLs). The formulation of FP 60-2 results in a 51 percent reduction in VOC content relative to FP 60. As a result, VOC emissions during production and repair processes will be significantly reduced on a per aircraft basis. FP 60-2 exhibited a greater build rate and decreased cure time relative to FP 60, which will lead to decreases in labor hours required for material application, overall material application time, and production/repair cycle time. FP 60-2 also showed a slight advantage relative to FP 60 with regard to the amount of material that is required to build up to a common thickness when applied over an identical area of substrate.

During this program, the durability of FP 60-2 in a simulated maritime environment was observed to be significantly superior to the durability of FP 60 in the same environment. This was an unexpected advantage of FP 60-2 relative to FP 60 that will result in significant reductions in the Life-Cycle Costs (LCC) and life-cycle VOC emissions of the WS of interest. As a result of the superior durability of FP 60-2 in maritime environments, the frequency of repairs and level of effort to make repairs, including labor hours and material usage, will be significantly decreased. Fewer repairs will also result in fewer VOC emissions and decreased downtime during the lifetime of the WS of interest.

The advantages of FP 60-2 relative to FP 60 are projected to result in LCC savings of \$49 million (in current-year dollars) over the next 40 years, a payback period of less than one year on funding contributions from ESTCP and DoD as a whole, and an Internal Rate of Return (IRR) of 49.5 percent and 36.9 percent for ESTCP and DoD, respectively. The 51 percent reduction in VOC content of FP 60-2 relative to FP 60 will result in significant life-cycle reductions in VOC and HAP emissions. It is estimated that life-cycle VOC and HAP emissions of the WS of interest will be reduced by 386,840 pounds and 447,625 pounds, respectively, by replacing FP 60 with FP 60-2 in production and PDM operations.

Additionally, as a result of this program, a few other materials that are formulated with the same resin as FP 60-2 (002 resin) have been transitioned to the WS of interest to replace baseline materials other than FP 60 formulated with the same resin that is used in FP 60 (001 resin). The resin of a material is largely responsible for its durability. When the superior durability of FP 60-2 relative to FP 60 in maritime environments became apparent, LM Aero and SPO managers made the decision to qualify and transition additional 002 resin-based materials other than FP 60-2 to replace additional baseline coatings formulated with the 001 resin other than FP 60 that were currently being applied to the WS of interest. Therefore, the environmental and economic benefits resulting from this program as summarized in this report are extremely conservative. The benefits to the WS of interest as a result of this program are expected to be orders of magnitude higher than the level of benefits summarized in this report due to the increased durability of the 002 resin in maritime environments compared to the durability of the 001 resin.

The testing and qualification of the additional 002 resin-based coatings other than FP 60-2 were performed under a separate Air Force program that ran parallel to this program. It was outside the scope of this ESTCP program to evaluate any coating other than FP 60-2 since it was not known until near the end of this program that the 002 resin would revolutionize the coating stack-up of the WS of interest.

STAKEHOLDER/END-USER ISSUES

In order for FP 60-2 to replace FP 60 in production and PDM processes, LM Aero and SPO engineers required that FP 60-2 pass all qualification testing per the relevant material specification and show environmental and economic advantages relative to FP 60. In addition to passing all material specification requirements, FP 60-2 demonstrated environmental and economic advantages relative to FP 60. These results have lead LM Aero and the relevant SPO to make the decision to transition FP 60-2 to the WS platform.

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1.0 TECHNOLOGY DESCRIPTION

1.1 TECHNOLOGY DEVELOPMENT AND APPLICATION

This program focused on improving upon a baseline aerospace coating in terms of environmental and application properties. The proposed technology to be described and discussed is an aerospace coating (FP 60-2) that has environmental, application, and durability advantages over existing aerospace coatings. This section will describe the key design criteria used in the formulation of FP 60-2 and a chronological summary of the development of this coating. Key design criteria considered during the formulation of FP 60-2 were Volatile Organic Compound (VOC) content and application time. The goals were to decrease the VOC content relative to the baseline coating (FP 60) and to decrease the time needed to build up to desired thickness and to reach full-cure.

To address lowering the VOC content, the FP 60-2 material supplier used solvents that are exempt by Environmental Protection Agency (EPA) standards. VOCs are defined as compounds that readily evaporate and react with other compounds in the atmosphere to form ozone. Examples of VOCs include xylene, toluene, and Methyl Ethyl Ketone (MEK). Exempt solvents are ones that do not readily react with other atmospheric compounds to form ozone and are therefore not considered VOCs by EPA standards. Examples of exempt solvents include Oxsol 100® and acetone. The solvents used in FP 60-2 are Methyl Propyl Ketone (MPK - non-exempt) and acetone (exempt). This solvent package gives FP 60-2 a VOC content of 213 g/L, compared to a 432 g/L VOC content of FP 60.

The use of acetone in the formulation of FP 60-2 was the main driver for the rapid deposition, quick curing nature of FP 60-2. The vapor pressure of acetone is relatively high (180 mmHg at 20°C), which allows much of it to evaporate prior to reaching the substrate when FP 60-2 is being sprayed. As a result of the relatively small quantity of acetone that reaches the substrate, vertical shrinkage of the wet material is minimized, which increases the effective (dry) build rate (mils/pass). This allows FP 60-2 to be built up to desired thickness much faster than FP 60. Additionally, since there is only a small quantity of acetone that reaches the substrate and since acetone has such a high vapor pressure, FP 60-2 quickly cures to the point that it is dry-to-sand. The dry-to-sand time is the time required for a coating to cure to the point that it can be sanded without gumming up or balling up. After a coating is dry-to-sand, the next important cure time metric is time-to-overcoat, which is the time required before a coating can have materials applied over it. The time-to-overcoat is largely an indication that solvent evaporation has slowed to the point that surface finishes of materials applied above it will not be adversely impacted by defects such as bubbling and orange peel caused by solvent evaporation. While actual time-to-topcoats of FP 60-2 and FP 60 were not determined during this program, the time from application of first coat to dry-to-sand time of final coat after being built up to a common thickness was determined for each coating. As results will show, FP 60-2 reaches this point much more quickly than FP 60, which is an indication that FP 60-2 can be topcoated much more quickly than FP 60 and will lead to decreased production and maintenance times.

The chronology of development of FP 60-2 began in the fall of 1999. A program was initiated out of the Air Force Research Laboratory, Materials and Manufacturing Directorate, Acquisition Systems Support Branch (AFRL/MLSC) at Wright-Patterson Air Force Base (WPAFB), OH to develop aerospace coatings characterized by low VOC content and decreased overall application time relative to existing baseline aerospace coatings. The AFRL program ended with the successful development

of two coatings that met all AFRL program goals. One coating was formulated with a supplier-designated 002 resin. When this ESTCP program began, Science Applications International Corporation (SAIC) worked with Lockheed Martin Aeronautics Company (LM Aero) and the material supplier to formulate FP 60-2 using the 002 resin as the base.

1.2 PROCESS DESCRIPTION

FP 60-2 was designed as a drop-in replacement for FP 60 since both coatings are admixed materials and can be applied with conventional manual spray and robotic spray systems. The full-scale application study performed during this program at Air Force Plant 4 (AFP 4), Ft. Worth, TX allowed LM Aero spray operators to become adequately familiar with the spray characteristics of FP 60-2 so that no additional training will be required once FP 60-2 is transitioned to production processes. Additionally, Northrop Grumman Corporation (Northrop) spray operators at AFP 42 will use Weapon System (WS) program funding to reprogram the robotic spray system to account for the improved application properties of FP 60-2 relative to those of FP 60, which the robotic spray system was initially programmed to spray. There are not expected to be any mobilization, installation, or training costs as part of the transition from FP 60 to FP 60-2. Since FP 60-2 is formulated with a lower VOC content than FP 60, there should be no new health and safety requirements that arise from replacing FP 60 with FP 60-2.

The following were key FP 60-2 design criteria:

- Significant reduction ($\geq 75\%$) of coating application times
- Significant reduction ($\geq 50\%$) in VOC content
- Drop-in replacement for existing coating (FP 60)

In order for FP 60-2 to be listed on the Qualified Products List (QPL) of the WS of interest, it was tested according to the material specification of the WS of interest. It was anticipated that FP 60-2 would have certain application advantages relative to FP 60. The application properties of FP 60-2 were compared to those of FP 60 during lab-scale and full-scale application studies. Finally, to compare the failure modes of FP 60-2 and FP 60, airflow testing was performed on both materials.

Material application should be positively impacted by FP 60-2 implementation due to the improved build rates and reduction in cure times. From a logistical standpoint, replacement of FP 60 with FP 60-2 is not expected to create any added personnel or training requirements. In addition, FP 60-2 requirements for Personal Protective Equipment (PPE) use will not exceed those of FP 60. The PPE requirement remains unchanged since FP 60-2 does not introduce any added HAPs or toxic chemicals, while reducing the amount of VOCs released.

1.3 PREVIOUS TESTING OF THE TECHNOLOGY

The 002 resin which acts as the base resin for FP 60-2 was formulated and initially tested in the form of a different type of material than FP 60-2 during a project funded by AFRL/MLSC at WPAFB, OH. This 002 resin-based material was downselected from a group of 9 initial materials formulated for low VOC content and quick cure times and tested thoroughly for physical, mechanical, and resistance properties. Based on the impressive environmental and performance results of this 002 resin-based material achieved during the AFRL program, the 002 resin was chosen as the base resin for FP 60-2.

1.4 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

Prior to the qualification of FP 60-2, FP 60 was the only coating that had been qualified to the WS material performance specification for application onto certain areas of the WS. The successful testing and qualification of FP 60-2 per the WS material performance specification has positioned FP 60-2 as currently the only existing and fully qualified alternative to FP 60. There are two other technologies in addition to FP 60-2 that are being tested as alternatives to FP 60. A mold-in-place coating is being tested as an alternative to replace a certain portion of FP 60 application during production processes. An Ultraviolet (UV) cure coating is being tested mainly as a repair material for FP 60. However, these technologies have not completed all qualification testing and are therefore currently not valid, qualified replacements for FP 60, and due to their special application methods, they would not be drop-in replacements for FP 60. Additionally, these alternatives may not have the same durability benefits relative to FP 60 that FP 60-2 has in maritime environments, which may not make these two other alternative technologies as attractive as FP 60-2 from the stand-point of Life-Cycle Cost (LCC) reductions relative to FP 60. Finally, FP 60-2 will replace FP 60 in its entirety during production processes at AFP 42 and AFP 4, while the other two potential alternatives are being evaluated to replace only certain portions of FP 60 during production processes or when repairs are required.

The advantages of FP 60-2 relative to FP 60 as demonstrated during this program are as follows:

- lower VOC content (213 g/L vs. 432 g/L)
- increased build rate (mils/pass)
- decreased cure time
- decreased material usage
- decreased overall application time
- increased durability

There are limitations to the degree of each of the stated advantages. The solvent package of FP 60-2 determines the VOC content, and to a large extent, the build rate, cure time, material usage, and overall application time. The types and quantities of solvents used in the formulation of FP 60-2 were governed by the requirements to formulate a low VOC coating with superior application and sprayability properties relative to FP 60. During the formulation of FP 60-2, the material supplier performed spray trials with various solvents to determine the types and quantities of solvents that would minimize VOC content, maximize build rate, and minimize cure time, material usage and overall application time while achieving a smooth, acceptable surface finish. The solvents used in the formulation of FP 60-2 consist of MPK and acetone. Acetone is an exempt solvent, which means it is not considered a VOC by EPA standards because it does not react with compounds in the lower atmosphere to form ozone. MPK is not an exempt solvent and is the main source of FP 60-2's VOC content. A complete shift to acetone in the formulation of FP 60-2 would have resulted in a VOC content of 0 g/L but would also have resulted in unacceptable surface finish (bubbling, significant orange peel) since acetone evaporates extremely rapidly. The addition of MPK results in a slower (but still relatively rapid) evaporation rate of acetone, which leads to a smoother, acceptable surface finish. The rapid evaporation rate of acetone leads to a relatively high build rate and quick cure time, where cure time is defined as dry-to-sand time. Consequently, the overall application time of FP 60-2, defined as the time from application of the first layer of FP 60-2 to the time when the final layer of FP 60-2 is dry-to-sand, is relatively low.

In terms of material usage, a lesser quantity of FP 60-2 is required to be sprayed to achieve a desired thickness over a given area of application relative to the amount of FP 60 required to achieve the same desired thickness over the same given area of application. It is speculated that this difference is related to the relatively low viscosity that FP 60-2 has relative to FP 60, which most likely results in a greater spray efficiency of FP 60-2 relative to FP 60, although spray efficiency was not evaluated during this project. For equal amounts of FP 60-2 and FP 60 that are sprayed, it is speculated that a greater percentage of the sprayed FP 60-2 resin reaches the substrate compared to the percentage of sprayed FP 60 resin that reaches the substrate. This leads to decreased material usage requirements for FP 60-2 relative to FP 60.

The durability of FP 60-2 is governed mainly by the type of resin used in its formulation. As described in the ESTCP Cost and Performance and Final Reports for the other material demonstrated during this program (FP 212, which will be applied to a different WS than FP 60-2), puffer box testing demonstrated the durabilities of the 002 resin (used in the formulation of FP 60-2) and of the 001 resin (used in the formulation of FP 60). It was shown that the 002 resin lasts 2 to 3 times longer than the 001 resin in a maritime-simulated environment. For more information on the puffer box test and results, refer to the ESTCP Cost and Performance and Final Report for FP 212 or to the technical report entitled *FP 212 Puffer Box Testing*, which describes this test and the test results in detail and is available from the Aeronautical Systems Center, Acquisition Environmental, Safety & Health Division, Pollution Prevention Branch (ASC/ENVV).

2.0 DEMONSTRATION DESIGN

2.1 PERFORMANCE OBJECTIVES

Table 1 presents the performance objectives for this effort and reports whether or not these objectives were met.

Table 1. Performance Objectives

Type of Performance Objective	Primary Performance Criteria	Expected Performance (Metric)	Actual Performance	Actual Performance Objective Met?
Quantitative	1. <i>Meet or exceed performance specification requirements</i>	Pass/Fail	Pass	Yes
	2. <i>Reduce overall application time</i>	≥ 75%	33% reduction	No
	3. <i>Reduce VOC content</i>	≥ 50%	51% reduction	Yes
	4. <i>Reduce Material Usage</i>	≥ 20%	18% reduction	No

The material performance results of FP 60-2 were acceptable and the VOC content was reduced more than the stated goals. FP 60-2 showed a reduction in overall application time and material usage relative to FP 60, just not to the extent of the expected performance.

2.2 SELECTING TEST PLATFORMS/FACILITIES

LM Aero facilities at AFP 4, Ft. Worth, TX and Northrop facilities in El Segundo, CA were selected to perform tests on FP 60-2. These sites were selected since they had the facilities and equipment necessary to complete all required testing and since LM Aero and Northrop conducted identical testing on FP 60 at these facilities prior to the start of this program. For consistency, the same sites and facilities were selected to test FP 60-2 as were used to test FP 60.

Lab-scale application studies were performed on FP 60-2 under this program and previously on FP 60 under a separate program by LM Aero and Northrop personnel at the El Segundo, CA facility. These studies involved applying the materials at 4 corners of a temperature/Relative Humidity (RH) envelope: high T/high RH, high T/low RH, low T/high RH, low T/low RH. Northrop's El Segundo facility has a spray laboratory with the capability to maintain the stringent temperatures and humidities that were required for this study.

Lab-scale testing per the WS performance specification and lab-scale airflow testing occurred at AFP 4. The LM Aero test facilities and test apparatuses at AFP 4 that were used to perform performance specification testing on FP 60 under a previous and separate program were used to perform performance specification testing on FP 60-2 under this program. The subsonic airflow test chamber located at AFP 4 was used by LM Aero to perform airflow testing on FP 60-2 and FP 60 under this program.

The full-scale application study performed on FP 60-2 and FP 60 under this program was performed at AFP 4 since the full-scale structure that was used was built and stored by LM Aero at AFP 4.

The WS for which FP 60-2 was demonstrated was chosen since LM Aero and Systems Program Office (SPO) managers had identified a need to decrease the VOC content and application time of the baseline coating, FP 60.

2.3 TEST FACILITY HISTORY/CHARACTERISTICS

The Northrop, El Segundo facility supports Northrop Grumman's Integrated Systems sector. At the El Segundo facility, Northrop designs, develops, produces and supports integrated systems for DoD applications, including aircraft. There will be no application of FP 60-2 to the WS of interest at the Northrop, El Segundo facility. As stated previously, the Northrop, El Segundo facility was chosen for the capabilities of its laboratories to tightly control temperature and humidity for the lab-scale application study.

Currently, FP 60 is applied by Northrop at AFP 42 and by LM Aero at AFP 4. AFP 42 and AFP 4 are Government-Owned, Contractor Operated (GOCO) facilities. At AFP 42, Northrop currently applies FP 60 to the WS of interest during production processes using a robotic spray system. The greatest benefit to AFP 42 of transitioning FP 60-2 will be decreased application time. The decreased VOC content of FP 60-2 relative to FP 60 will have minimal impact to AFP 42 VOC emissions since the facility that Northrop operates at AFP 42 has installed Best Available Control Technology (BACT) that captures and destroy 95 percent of the VOCs emitted during production processes. At AFP 4, LM Aero currently applies FP 60 to the WS of interest during final finish processes using manual spray equipment. Similarly to AFP 42, AFP 4 will benefit from the decreased application time of FP 60-2 relative to FP 60. Unlike AFP 42, AFP 4 will benefit from the decreased VOC content of FP 60-2 since AFP 4 does not possess VOC destruction control technology.

FP 60-2 will be applied to the WS of interest by Northrop at AFP 42 using a robotic spray system and by LM Aero at AFP 4 using manual spray equipment. FP 60-2 will be a drop in replacement for FP 60 in the current spray systems at each facility.

2.4 PHYSICAL SET-UP AND OPERATION

FP 60-2 will be transitioned to production processes at AFP 42, where it will be applied to the WS of interest using the robotic spray system that is currently in operation at the Northrop-operated facility at AFP 42. Since FP 60-2 is an admixed material, it will be a drop-in replacement for FP 60. The WS SPO is currently funding production acceptance testing of FP 60-2, which includes performing spray optimization studies of FP 60-2 using the robotic spray system. Northrop may have to reprogram the robotic spray settings/patterns due to the greater build rate and quicker cure of FP 60-2 relative to FP 60.

FP 60-2 will be transitioned by LM Aero to final finish processes at AFP 4 as a drop-in replacement for FP 60, which is currently applied using manual spray equipment. LM Aero became familiar with the application properties of FP 60-2 during the lab-scale and full-scale application studies, which required FP 60-2 to be applied to vertically-mounted test panels and a full-scale engineering prototype, respectively, using hand-held spray equipment. As such, minimal training will be required to transition FP 60-2 to final finish processes. The information generated during the lab-scale and full-scale application studies performed as part of this program will aid Northrop during the robotic spray optimization study at AFP 42. Detailed

summaries of the lab-scale and full-scale application studies are available in technical reports entitled *FP 60-2 Laboratory-Scale Application Study* and *FP 60-2 Full-Scale Application Study*, respectively, and can be obtained from ASC/ENVV.

The various FP 60-2 demonstration efforts were conducted over the course of 28 months and included a lab-scale application study, lab-scale testing per the WS performance specification, airflow testing, and a full-scale application study.

2.5 SAMPLING/MONITORING PROCEDURES

This section describes parameters that were monitored and monitoring methods that were used while material was being sprayed during lab-scale and full-scale application studies. Monitoring procedures during material application were critical during the lab-scale and full-scale application studies in order to assess key application properties, such as build rate and time between passes. Monitoring material application during test specimen preparation for airflow testing, lab-scale testing per the WS material performance specification, and puffer box testing were not of particular importance, other than to ensure that test specimen preparation procedures were being followed to prepare proper test panels. As such, monitoring procedures used during test panel preparation for airflow testing, lab-scale testing per the WS material performance specification, and puffer box testing will not be discussed.

Northrop and LM Aero conducted a lab-scale application study of FP 60-2 at the Northrop facility in El Segundo, CA to test application rates at the “envelope” temperature/RH conditions. The objective of this study was to determine the performance of application properties of FP 60-2 under different temperature and humidity conditions and to compare these results to the results of this same study performed previously on FP 60 by LM Aero and Northrop under a separate project. During this study, Northrop and LM Aero engineers closely monitored the application properties of FP 60-2 as it was applied to vertically mounted panels under different temperature and humidity conditions. The performance parameters of interest that were monitored during material application are located in Table 2.

Table 2. Laboratory-Scale Application Study Monitoring

Performance Parameter	Monitoring Frequency	Monitoring Method	Demo Plan Deviations
Application temperature	Continuously during sample stack-up	Spray booth thermostat	None
Application humidity	Continuously during sample stack-up	Spray booth humidistat	None
Wet mils per pass	Once after each spray pass	Wet mil gauge	None
Time between passes	Between each spray pass	Time tracking	None
Wet coating performance (formation of sags, runs, drips)	During each spray pass	Qualitative visual inspection	None
Total application time	Once during each spray-up	Time tracking	None
Total number of passes	Each pass tallied	Visually	None

After the panels were prepared during this study, they were shipped to AFP 4, where LM Aero conducted limited tests on the cured panels to evaluate the properties of the cured panels (procedures and results of this testing are discussed later in Section 3.6 *Analytical Procedures*).

During the maximum build rate study performed on FP 60-2 and FP 60, which was performed by LM Aero at AFP 4 on vertically-mounted square panels prior to material application to the full-scale prototype, monitoring was completed for the performance parameters listed in Table 3. The objective of this study was to determine the maximum build rate of FP 60-2 and FP 60 under “normal” laboratory temperature and humidity conditions (approximately 78°F and 60% RH). These environmental conditions approximate the environmental conditions that will be present during FP 60-2 application at AFP 4. Full-scale spray equipment was used to complete this study. The maximum build rate established in this study was used in the full-scale application study.

Table 3. Maximum Build Rate Study Monitoring

Performance Parameter	Monitoring Frequency	Monitoring Method	Demo Plan Deviations
Application temperature	Continuously during build rate trial	Spray booth thermostat	None
Application humidity	Continuously during build rate trial	Spray booth humidistat	None
Wet mils per pass	Once after each spray pass	Wet mil gauge	Extreme wet thickness once (~20 mils)
Time between passes	Between each spray pass	Time tracking	None
Wet coating performance (formation of sags, runs, drips)	During each spray pass	Qualitative visual inspection	None
Total wet material thickness	After application of final pass	Wet mil gauge	None

During the full-scale application study performed by LM Aero at AFP 4 on FP 60-2 and FP 60, monitoring was accomplished for the listed performance parameters according to the following schedule in Table 4. The objective of this study was to use the max build rates determined for each material during the max build rate study to provide a side-by-side comparison of the application performances of FP 60-2 and FP 60 under “normal” laboratory temperature and humidity conditions (approximately 78°F and 60% RH). These environmental conditions approximate the environmental conditions that will be present during FP 60-2 application at AFP 4. Full-scale production spray equipment was used during this study to apply FP 60-2 and FP 60 to a full-scale engineering prototype of one of the proposed FP 60-2 application areas of the WS of interest.

Table 4. Full-Scale Prototype Application Study Monitoring

Performance Parameter	Monitoring Frequency	Monitoring Method	Demo Plan Deviations
Application temperature	Continuously during prototype trial	Spray booth thermostat	None
Application humidity	Continuously during prototype trial	Spray booth humidistat	None
Volume of mixed material	Once during each kit mixed	Inventory tracking	None
Wet mils per pass	Once after each spray pass	Wet mil gauge	None
Time between passes	Between each spray pass	Time tracking	None
Wet coating performance (formation of sags, runs, drips)	During each spray pass	Qualitative visual inspection	None
Total wet material thickness	After application of final pass	Wet mil gauge	None
Total application time	Once during each spray-up	Time tracking	None
Total number of passes	Each pass tallied	Visual	None
Volume of material used	Once after each spray-up	Weight change of spray equipment	None
Volume of waste material	Once after each spray-up	Weight change of spray equipment	None
Spray equipment cleaning time	Once after each spray-up	Time tracking	None
Volume of solvent used	Once after each spray-up	Inventory tracking	None

2.6 ANALYTICAL PROCEDURES

The cured material parameters that were evaluated during all phases of testing are discussed in this section.

Several test procedures, outlined in Table 5, were used to test the panels of FP 60-2 that were prepared in El Segundo during the lab-scale application study. Once the panels had fully cured in El Segundo, they were shipped to AFP 4, where LM Aero evaluated the properties in Table 5.

Table 5. Laboratory-Scale Application Study Analytical Procedures

Analytical Test Procedure	Test Method	Demo Plan Deviations
Cured coating hardness	ASTM D 2240	None
Cured specific gravity	ASTM B 923-02	None
Ultimate tensile strength	ASTM D 412	None
Elongation at break	ASTM D 412	None
Dry mils thickness	ASTM D 1005	None
Thermo-gravimetric analysis	LM Aero method	None
Photo microscopy	Qualitative visual inspection	None

Evaluation of subsonic airflow on induced coating failures for panels of FP 60-2 and FP 60 were performed. The objective of this task was to determine if induced failures in panels of each material would propagate when acted upon by airflow and to determine the failure mode of each material. Should either material fail in the form of complete delamination from test panels, this would be cause for concern. Table 6 contains a summary of airflow qualitative test procedures.

Table 6. Airflow Test Analytical Procedures

Analytical Test Procedure	Test Method	Demo Plan Deviations
Airflow testing of induced coating failures (delamination, failure propagation)	LM Aero method (Qualitative visual inspection)	None

Table 7 contains the analytical procedures that were utilized for material properties testing of FP 60-2 performed by LM Aero at AFP 4. The objective of this testing was to evaluate FP 60-2 according to the material performance specification of the WS of interest. This testing was required in order to list FP 60-2 on the QPL of the WS of interest.

Table 7. Weapon System Material Performance Specification Analytical Procedures

Analytical Test Procedure	Test Method	Demo Plan Deviations
Storage stability	Vendor test (Product guarantee)	None
Condition in container	FED-STD-141D Method 3011.3	None
Weight per gallon	ASTM D 1475	None
Non-Volatile Content	ASTM D 2369	None
Viscosity	ASTM D 2196	None
Pot life	ASTM D 2196	None
Cured coating hardness	ASTM D 2240	None
Cured specific gravity	ASTM B 923-02	None
Ultimate tensile strength	ASTM D 412	None
Elongation at break	ASTM D 412	None
Flatwise tensile adhesion	ASTM D 4541	None
Roller peel adhesion*/T-peel adhesion	ASTM D 3167 */ ASTM 1876	Lowered the elevated test temperature/performed T-peel test
Low temperature flexibility	ASTM D 522	None
Intercoat adhesion	ASTM D 4541	None
Chemical rub resistance	ASTM D 5402	None
Fluid emersion resistance	Defined within performance spec.	None
Heat resistance	AMS 3065	None
Corrosion resistance	ASTM B 117 ASTM G85	None
Humidity resistance	ASTM D 2247	None
* Original test method failed to produce conclusive results		

Table 8 outlines the analytical procedures that were completed as part of the maximum build rate study performed on FP 60-2 and FP 60 by LM Aero at AFP 4.

Table 8. Maximum Build Rate Study Analytical Procedures

Analytical Test Procedure	Test Method	Demo Plan Deviations
Tack-free time	LM Aero method	None
Dry-to-sand time	LM Aero method	None
Total dry mils thickness	ASTM D 1005	None
Coating surface appearance	Qualitative visual inspection	None

Table 9 outlines the analytical procedures that were completed as part of the full-scale prototype application study performed on FP 60-2 and FP 60 by LM Aero at AFP 4.

Table 9. Full-Scale Prototype Application Study Analytical Procedures

Analytical Test Procedure	Test Method	Demo Plan Deviations
Tack-free time	LM Aero method	None
Dry-to-sand time	LM Aero method	None
Dry mils thickness	ASTM D 1005	None
Coating surface appearance	Qualitative visual inspection	None

An additional test that is relevant for assessing the performance of FP 60-2 is puffer box testing. This test evaluates the temperatures, pressures, and exposures that a material experiences when located on certain portions of an aircraft operating continuously in a maritime environment. The puffer box test article, with the materials applied to it, is subjected to humidity and salt fog exposure, followed by pressure testing, and ends with thermal cycling. This cycle of exposures comprises one block of puffer box testing. Eight total blocks are required for a full evaluation and simulate the exposures and stresses that a coating stack-up would experience on an aircraft operating continuously in a maritime environment for an entire lifetime of 30 years. After each block, the coatings on the test article are visually assessed for any signs of degradation. If coatings degrade significantly prior to completion of the 8th block of puffer box testing, they are repaired, and testing continues. This test provided an accurate correlation to how long the coating would last on an aircraft operating in a maritime environment.

Puffer box testing was not conducted on FP 60-2. Instead, as part of this overall program, puffer box testing was conducted on FP 212, which is formulated with the 002 resin, and on a legacy material, which is formulated with the 001 resin. Like FP 212, FP 60-2 is formulated with the 002 resin, and like the legacy material, FP 60 is formulated with the 001 resin. Since the resin is largely responsible for a coating's durability, the puffer box results for FP 212 and the legacy material are relevant for assessing the durabilities FP 60-2 and FP 60, respectively. A summary of the puffer box testing performed on FP 212 and the legacy material will be summarized in this report and in the ESTCP reports for FP 212. Detailed descriptions of puffer box testing and results are available in the report entitled, *FP 212 Puffer Box Testing*, which is available from ASC/ENVV. Table 10 lists analytical procedures performed during puffer box testing.

Table 10. Puffer Box Test Analytical Procedures

Analytical Test Procedure	Test Method	Demo Plan Deviations
Puffer Box testing of coating systems (Coating durability)	LM Aero method (Qualitative visual inspection)	None

3.0 PERFORMANCE ASSESSMENT

3.1 PERFORMANCE DATA

A summary of the test results from the laboratory-scale application study of FP 60-2 is located in Table 11. For a detailed description of the materials and methods used, results, conclusions, and recommendations from this testing, refer to the report entitled *FP 60-2 Laboratory-Scale Application Study*, which is available from ASC/ENVV.

Table 11. FP 60-2 Laboratory-Scale Application Study Results Summary

Spray Conditions and Methods*	Total Process Time (hours) to Achieve Final Dry Material Thickness / and Total Process Time (hours) to Achieve Desired Dry Material Thickness (calculated using effective build rate)**	Surface Finish
Build Rate A; 5 minute dwell time		
65°F / 45% RH	N/A	Significant dripping/panel was not finished
85°F / 70% RH	3.8 / 3.1	Slight orange peel/dripping at bottom
85°F / 45% RH	4.2 / 3.9	Slight orange peel
65°F / 70% RH	4.2 / 4.4	Slight orange peel/dripping at bottom
Build Rate B; 5 minute dwell time		
85°F / 70% RH	4.7 / 4.8	Slight orange peel
85°F / 45% RH	6.3 / 5.9	Slight orange peel
65°F / 45% RH	6.3 / 6.3	Slight orange peel/dripping at bottom
65°F / 70% RH	6.3 / 6.5	Slight orange peel
Build Rate A; 10 minute dwell time		
65°F / 45% RH	8.3 / 8.3	Slight orange peel
65°F / 70% RH	8.3 / 9.2	Slight orange peel
85°F / 45% RH	8.3 / 9.8	Slight orange peel
85°F / 70% RH	8.3 / 9.8	Slight orange peel
Build Rate B; 10 minute dwell time		
65°F / 45% RH	12.5 / 12.5	Slight orange peel
65°F / 70% RH	12.5 / 13.3	Slight orange peel
85°F / 45% RH	12.5 / 13.3	Slight orange peel
85°F / 70% RH	12.5 / 13.8	Slight orange peel

*Build Rate A is greater than Build Rate B

**See paragraph following this table

In Table 11, the data included in the middle column on the left side of the slash reports how long it took to build up to the final dry thickness of each panel. However, each panel had a different average dry thickness. In order to make a valid comparison of the application time of each material, the data was normalized by choosing a desired thickness (referred to in Table 11 as the Desired Dry Material Thickness), and the length of time it would take to build each material up to the Desired Dry Material Thickness using the effective build rate (dry mils per pass) was calculated. The time required to build up to the Desired Dry Material Thickness using the effective build rate is included on the right side of the slash in the middle column of Table 11. For information on the effective build rate of each material refer to the report entitled *FP 60-2 Laboratory-Scale Application Study*, available from ASC/ENVV.

The data in Table 11 provides a good indication of the application tolerances of FP 60-2. Applying FP 60-2 with 10 minutes between passes provides better surface finish than waiting only 5 minutes between each pass. Applying FP 60-2 using Build Rate B (lower build rate) generally leads to better surface finish than applying FP 60-2 with Build Rate A (higher build rate). These results are comparable to the results of this same study performed on FP 60 years ago, according to LM Aero engineers who participated in this study and in the same study performed on FP 60-2 during this ESTCP Program. It was observed during this study that applying FP 60-2 under elevated temperature and humidity conditions (85°F / 70% RH) increases the build rate and decreases the overall application time. However, these elevated temperature and humidity conditions are not typical of most production environments where FP 60-2 will be applied. The results in Table 11 are acceptable and supported further evaluation of FP 60-2.

Once the panels described in Table 11 had fully cured, they were shipped to AFP 4, where LM Aero tested the panels for selected material properties. Table 12 lists the tests that were performed on the panels. The actual test results will not be included in this report but are available in the technical report entitled *FP 60-2 Laboratory-Scale Application Study*, which is available from ASC/ENVV.

Table 12. Material Property Testing of Panels Prepared During Lab-Scale Application Study

Category	Panel Conditions	Outcome
Average cured coating hardness (Shore A)	After 4 hours w/ 5 min dwell time	Not included in this report
	After 4 hours w/ 10 min dwell time	Not included in this report
	After 5 days w/ 5 min dwell time	Not included in this report
	After 5 days w/ 5 min dwell time	Not included in this report
Cured specific gravity		Not included in this report
Average ultimate tensile strength (PSI)	RT w/ 5 min dwell time	Not included in this report
	RT w/ 10 min dwell time	Not included in this report
	275 °F w/ 5 min dwell time	Not included in this report
	275 °F w/ 10 min dwell time	Not included in this report
Average Percent Elongation	RT w/ 5 min dwell time	Not included in this report
	RT w/ 10 min dwell time	Not included in this report
	275 °F w/ 5 min dwell time	Not included in this report
	275 °F w/ 10 min dwell time	Not included in this report
Thermo-gravimetric analysis		Not included in this report
Photo microscopy		Not included in this report

There were no threshold performance values selected for the physical and mechanical property tests performed since the laboratory application study was not designed to qualify FP 60-2 to a specific material specification. Instead, results were used to explore the application capabilities of FP 60-2 at various temperature and humidity conditions and to compare them to the known performance characteristics of FP 60. Analysis of the application study results suggests that FP 60-2 has application properties that are slightly better than FP 60, especially when applied under elevated temperature and humidity conditions. Test data also demonstrates that longer dwell time between passes impacts some of the coating's performance characteristics, specifically coating hardness, density, tensile strength, and flexibility. Overall, the results of this laboratory-scale application study were positive and justified further testing and analysis of FP 60-2.

Table 13 presents a summary of the results from airflow testing of both FP 60-2 and FP 60. For a detailed description of the materials and methods used, results, conclusions, and recommendations from this testing, refer to the report entitled *FP 60-2 Airflow Testing* available from ASC/ENVV.

Table 13. Summary of Airflow Testing Results

Coating System and Pre-Conditioning	Outcome (Pass/Fail)
FP 60 with no conditioning	Pass
FP 60 with 7-day JP8 Bath at 140°F	Pass
FP 60-2 with no conditioning	Pass
FP 60-2 with 7-day JP8 Bath at 140°F	Pass

These results demonstrate that FP 60-2 performs well in high airflow conditions even after exposure to various environments. Simulated coating discrepancies did not propagate or cause more catastrophic coating failures. The FP 60-2 failure mode observed during testing is acceptable. The performance is also comparable to the baseline material, FP 60.

FP 60-2 was tested for all properties listed in the material specification of the WS of interest. The results from this testing are summarized in Table 14. For a detailed description of the materials and methods used, results, conclusions, and recommendations from this testing, refer to the report entitled *FP 60-2 Material Properties Testing* which is available from ASC/ENVV.

Table 14. Summary of FP 60-2 Material Properties Testing Results

Category	Result
Weight per Gallon (lb)	Acceptable
Non-Volatile Content (Weight %)	Acceptable
Viscosity, Initial (cps)	Lower than goal / Acceptable
Viscosity, Terminal (cps)	Lower than goal / Acceptable
Pot Life	Acceptable
4-Hour Cured Coating Hardness (Shore A Hardness)	Acceptable
5-Day Cured Coating Hardness (Shore A Hardness)	Lower than goal / Acceptable
Cured Specific Gravity	Acceptable
Average Tensile Strength (PSI) at elevated temperature	Lower than goal / Acceptable
Average Tensile Strength (PSI) at RT	Acceptable
Average Tensile Strength (PSI) at lowered temperature	Acceptable
Averaged Percentage of Elongation at elevated temperature	Acceptable
Averaged Percentage of Elongation at RT	Acceptable
Averaged Percentage of Elongation at lowered temperature	Lower than goal / Acceptable
Average Flatwise Tensile Adhesion (PSI)	Acceptable
Average Roller Peel Adhesion (lb/in. width)	Inconclusive results
Average T-Peel Adhesion Strength (lb/in.)	Acceptable
Low Temperature Flexibility	Acceptable
Average Intercoat Adhesion (PSI) for Aluminum, control	Acceptable
Average Intercoat Adhesion (PSI) for Aluminum, heat cycle	Acceptable
Average Intercoat Adhesion (PSI) for Composite, control	Acceptable
Average Intercoat Adhesion (PSI) for Composite, heat cycle	Acceptable
Chemical Rub Resistance	Acceptable

Based on the results and LM Aero review of the results, even though FP 60-2 did not meet all of the goals specified in the material specification, FP 60-2 test data is comparable to data from the same tests performed on FP 60, which has already been qualified for the weapon system of interest. Therefore, FP 60-2 test results were acceptable. The only notable difficulties occurred during roller peel adhesion testing of FP 60-2. During roller peel adhesion testing, the mode of failure of the test specimen is recorded. Table 15 lists the possible modes of failure.

Table 15. FP 60-2 Roller Peel Failure Mode Descriptions

Failure Mode Letter Designations	Failure Mode Description
A	Cohesive failure within FP 60-2 coating
B	Adhesive failure between screen and FP 60-2
C	Adhesive failure of primer to substrate
D	Adhesive failure of basecoat to primer
E	FP 60-2 to basecoat failure
F	Cohesive failure within basecoat
G	Air pockets

The objective of this roller peel adhesion test is to determine whether or not the cohesive strength of FP 60-2 (indicated by Failure Mode A) meets the numeric goals for lbs./in width stated in the material specification of the WS of interest when tested at Room Temperature (RT) and at elevated temperature. The objective can be accomplished if the following occurs:

1. If there is cohesive failure (Failure Mode A) within the layer of FP 60-2 below the mesh (indicated by the presence of FP 60-2 on the bottom of the mesh after it is peeled) the force necessary to cause this failure is a direct measure of cohesive strength and a pass/fail determination can be made.
2. If the mode of failure is not cohesive (any failure mode other than Failure Mode A), then as long as the force necessary to cause failure is equal to or greater than the goal for this test at RT and elevated temperature, it can be concluded that the cohesive strength of FP 60-2 is greater than the goals for this test.

However, if the mode of failure is not cohesive and the force necessary to cause failure is lower than the goals for this test, then it cannot be concluded whether or not FP 60-2 has met the stated goals for cohesive strength at RT and elevated temperature.

For the test specimens tested at elevated temperatures, 91 percent of the test specimens failed at the screen/FP 60-2 interface (Mode B) at a force less than the goal for this test. As a result, the test results for roller peel testing were for the most part inconclusive at elevated temperature. After several iterations of inconclusive roller peel testing using multiple test specimen preparation methods and performing this test at a lowered test temperature, T-peel testing was performed on FP 60-2 since the T-peel test evaluates the same properties as the roller peel test. During T-peel testing, the extent of cohesive failure (Failure Mode A) of the FP 60-2 test specimens was sufficient enough to conclude that the cohesive strength of FP 60-2 was being evaluated, and the average force to cause the failure was acceptable. The FP 60-2 test results support a decision to add FP 60-2 to the QPL of the WS of interest.

Results from the maximum build rate studies are summarized in Table 16. For a detailed description of the materials and methods used, results, conclusions, and recommendations from this testing, refer to the report entitled *FP 60-2 Full-Scale Application Study* available from ASC/ENVV.

Table 16. Summary of Maximum Build Rate Study Results

Build Rate Designations*	Outcome on Vertical Panels	
	FP 60	FP 60-2
A	Ended after 6 passes due to sagging and dripping	Ended after 5 passes due to sagging and dripping
B	Ended after 3 passes due to sagging and dripping	Material applied to desired wet thickness; significant dripping observed
C	Ended after approximately 30 passes due to dripping	Material applied to desired wet thickness; no dripping or sagging
D	Material applied to desired wet thickness; insignificant dripping	Material applied to desired wet thickness; no dripping or sagging

*Listed in order of decreasing build rate (mils/pass); A is the highest build rate, D is the lowest build rate

As Table 16 shows, the materials were applied at decreasing build rates on vertical panels until excessive dripping or sagging occurred, at which point spraying ended, or until desired thickness was achieved. The materials were evaluated for any signs of sagging or dripping or any other unacceptable application performance. The maximum build rate was determined as the build rate at which FP 60 and FP 60-2 could be applied while yielding acceptable application properties. As Table 16 shows, the maximum build rate designations for FP 60 and FP 60-2 were D and C respectively, indicating that the maximum build rate of FP 60-2 is higher than FP 60. This study was performed under normal laboratory temperature and humidity conditions, which mimics the conditions that will be present during FP 60-2 application in production environments. Results from the lab-scale application study, and from observations and other studies performed by LM Aero, suggest that if FP 60-2 is applied under elevated temperature and humidity conditions, the build rate is greater and the cure time is quicker than when applied under normal conditions.

Using the maximum build rates, FP 60 and FP 60-2 were applied to a full-scale engineering structure using full-scale production spray equipment, and data was collected. One material was applied at a time and then peeled off of the full-scale structure (a release agent was applied to the substrate prior to each spray trial so materials could be easily removed at the conclusion of each spray trial). This process was performed 3 times for each material so that average values for the data collected during material application could be calculated. Each iteration of material application to the full-scale engineering prototype resulted in different wet mil and dry mil thicknesses. In order to make valid comparisons of the application properties of FP 60 and FP 60-2 the data was normalized by calculating the results on a wet mil and dry mil basis. The averaged results from the full-scale structure application studies are summarized in Table 17 in terms of the level of advantage that FP 60-2 showed relative to FP 60. For a detailed description of the materials and methods used, results, conclusions, and recommendations from this testing, refer to the report entitled *FP 60-2 Full-Scale Application Study* which is available from ASC/ENVV.

Table 17. Summary of Averaged Full-Scale Application Study Results

Parameter	Percent Advantage of FP 60-2 Relative to FP 60
Build Rate	
Wet Build Rate	32.1% increase
Effective (Dry) Build Rate	56.5% increase
Vertical Shrinkage ¹	39.8% decrease
Application Time²	
Total Application Time per Wet Mil	21.3% decrease
Total Application Time per Average Dry Mil	33.2% decrease
Cure Time	
Dry-to-Sand Time	56.9% decrease
Application Time and Cure Time Combined	
Total time from Start of Application to Dry-to-Sand per wet mil	32.1% decrease
Material Usage	
Total Amount of Material Sprayed per Wet Mil	5.4% decrease
Total Amount of Material Sprayed per Average Dry Mil	18.2% decrease

¹Based on final wet material thickness and final dry material thickness

²Start of material application to completion of final pass

The most significant application advantages of FP 60-2 compared to FP 60 are the effective build rate (56.5 percent increase) and dry-to-sand time (56.9 percent decrease), which lead to a 32.1 percent decrease in the time it takes to build FP 60-2 up to desired thickness and reach dry-to-sand on a wet mil basis. These advantages should lead to significant decreases in production, Programmed Depot Maintenance (PDM), and field repair flow times and associated labor hours. The decrease in material usage should lead to decreased material costs, assuming FP 60-2 does not cost more per gallon than FP 60, which it currently does not. Additionally, the decreased overall application time is expected to result in a significant capital cost avoidance. In order to meet production goals, Northrop will build additional spray booths at AFP 42, Palmdale, CA. Northrop production flow modeling indicates that the improved FP 60-2 application properties will decrease the number of additional required spray booths by one. Thus, the costs of building an entire spray booth will be eliminated by implementing FP 60-2.

Since full-scale production equipment and full-scale structures were used during this study, the results require no extrapolation to what should occur during production and PDM processes; these results are highly accurate and representative of what should occur during production and PDM activities. The advantages of FP 60-2 relative to FP 60 that were revealed during the full-scale application study support the implementation of FP 60-2 into production, PDM, and field repair processes. As mentioned earlier in this report, FP 60-2 would have shown even greater application advantages relative to FP 60 had the temperature and humidity been elevated during this study. The environmental conditions during this study are representative of normal production environment conditions at AFP 42 and AFP 4.

The final performance data for FP 60-2 are the puffer box test results. As described in Section 3.6 *Analytical Procedures*, puffer box testing results are valid for FP 60-2 and FP 60 since this test was performed on FP 212 and a legacy material, and FP 60-2 and FP 60 are formulated with the same resins as FP 212 and the legacy material, respectively. After the fourth block of testing, the legacy material had degraded to the point that the majority of it had to be repaired prior to the start of the fifth block of testing. By the end of the seventh block of testing, the legacy material had again degraded to the point that the majority of it needed to be repaired. Puffer box testing then continued through 3 additional blocks of testing, for a total of 10 blocks. The FP 212 material showed virtually no degradation during puffer box testing. Figures 1 and 2 shows the puffer box after the completion of block 4, which is reasonably approximate to 15 years of operation in a maritime environment.

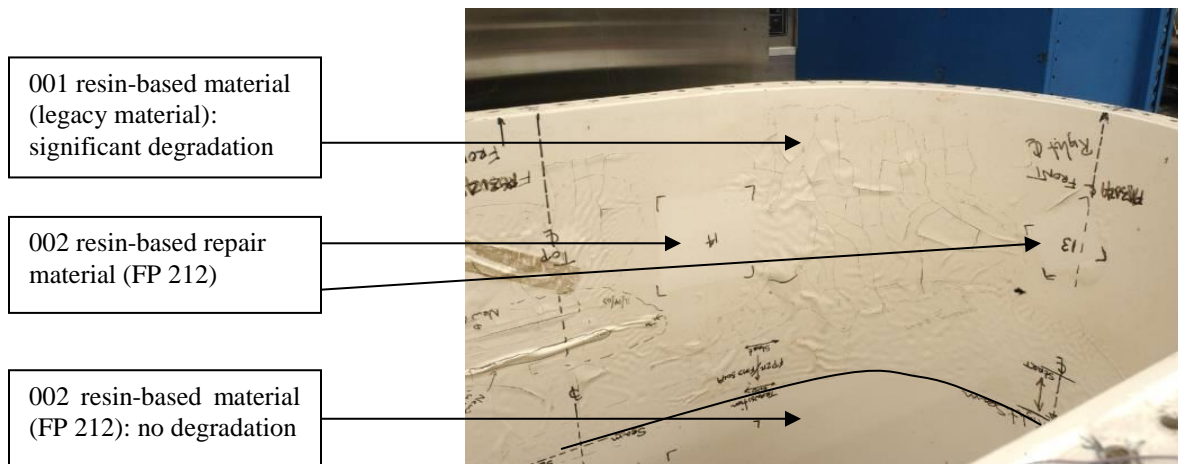


Figure 1. Puffer Box After Block 4

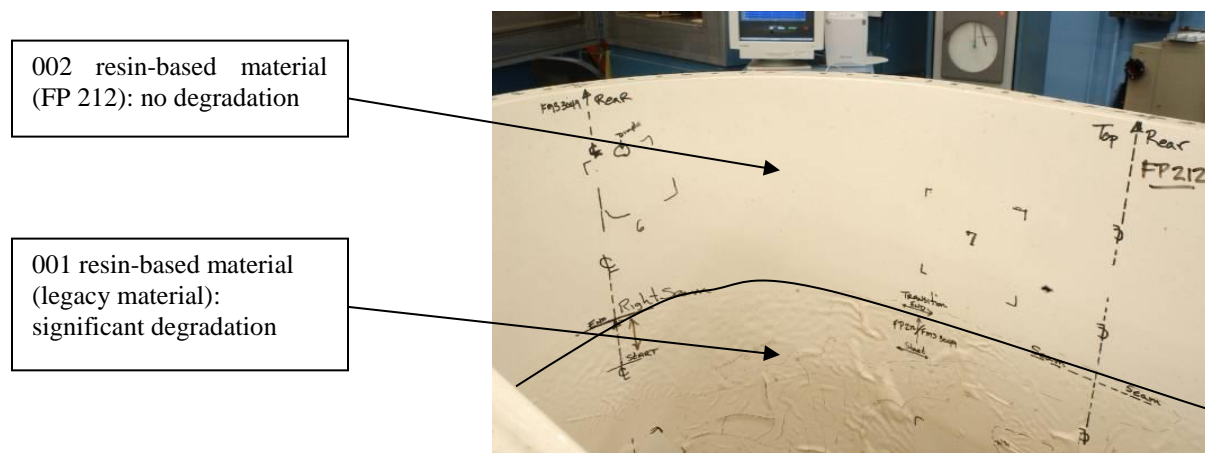


Figure 2. Puffer Box After Block 4

In Figures 1 and 2, the visible layer of material is a material applied over FP 212 and the legacy material. The only difference in the material stack-ups of the puffer box on each side of the black dividing line in Figures 1 and 2 is either FP 212 or the legacy material. As a result, the degradation seen in Figures 1 and 2 can be solely attributed to either FP 212 or the legacy material. Figure 1 shows significant cracking and blistering of the legacy material that is formulated with the 001 resin, which is the same 001 resin used in the formulation of FP 60. The unblemished 002 resin-based material (FP 212) is shown in Figure 1 in repair patches made in the midst of the legacy material and below the black dividing line between the legacy material and FP 212. Figure 2 is a picture of the puffer box that has been turned over to give a better view of the unblemished, undegraded FP 212 material which is formulated with the same 002 resin that is used in the formulation of FP 60-2. By the end of the tenth block of testing, FP 212 looked nearly the same as it does in Figures 1 and 2.

It needs to be stressed that the legacy material is not an unacceptable material; it has been operating on a legacy WS for multiple years. Figures 1 and 2 simply show that 002 resin-based materials are more durable in maritime environments than 001 resin-based materials. The legacy WS does not primarily operate in maritime environments so durability of the legacy material in a maritime environment is not as much of a concern as it is for FP 60-2, which will be applied to aircraft that operate primarily in maritime environments.

Puffer box test results indicate that the 002 resin lasts 2 to 3 times longer on an aircraft operating in a maritime environment than the 001 resin currently used in the baseline coatings that FP 212 and FP 60-2 will replace. According to LM Aero engineers, the puffer box test has a high degree of accuracy in terms of the overall exposures and stresses that a material will experience when applied to an actual aircraft operating in a maritime environment. The 001 resin degradation observed in the puffer box correlates extremely well with degradation observed in 001 resin applied to legacy aircraft operating in maritime environments. The increased durability of the 002 resin will result in significant environmental and LCC reductions for the WS of interest as the number of repairs required on aircraft operating in maritime environments will be significantly reduced. The puffer box test results were a major factor for making the decision to replace FP 60 with FP 60-2. For a detailed description of the materials and methods used, results, conclusions, and recommendations from this testing, refer to the report entitled *FP 212 Puffer Box Testing* available from ASC/ENVV.

3.2 PERFORMANCE CRITERIA

Table 18 lists the performance criteria that were developed during completion of the Demonstration Plan for this program.

Table 18. Performance Criteria

Performance Criteria	Description	Primary or Secondary
Product Testing	<i>1. Must meet or exceed all goals per the WS material performance specification</i>	<i>Primary</i>
Hazardous Materials	<i>Measure VOC content of FP 60-2 and compare to FP 60</i>	<i>Primary</i>
Ease of Use	<i>1. Assess sprayability and application capabilities during lab-scale application study</i> <i>2. Compare maximum application properties to baseline coating during full-scale application study</i> <i>3. Assess material usage</i> <i>4. Drop-in replacement for FP 60</i>	<i>Primary</i>
Versatility	<i>Ensure technical interchange with other weapon systems offices interested in 002 resin-based coatings</i>	<i>Secondary</i>

Table 19 outlines the actual performance criteria that were used to assess FP 60-2 and the methods used to confirm the performance of FP 60-2.

Table 19. Expected and Actual Performance Criteria and Performance Confirmation Methods

Expected Performance Criteria	Expected Performance Metric	Performance Confirmation Method	Actual Performance Criteria
PRIMARY CRITERIA (Performance Objectives) (Quantitative)			
Product Testing	<i>Meet or exceed all WS goals for performance</i>	<i>Per ASTM methods in WS performance specification</i>	Product Testing
Hazardous Materials	<i>Reduce VOCs by 50%</i>	<i>Per ASTM methods in WS performance specification</i>	Hazardous Materials
Ease of Use - Cure time - Build rate - Sprayability - Overall application time - Material usage	<i>Prove to have similar sprayability properties to FP 60</i> <i>Reduce overall application time by 75%</i> <i>Reduce material usage by 20%</i> <i>Prove to be a drop-in replacement for FP 60</i>	<i>Monitor and measure sprayability, application properties, and material usage during lab-scale and full-scale application studies</i>	Ease of Use - Cure time - Build rate - Sprayability - Overall application time - Material usage
SECONDARY PERFORMANCE CRITERIA (Qualitative)			
Versatility	<i>Increase interest in and achieve risk reduction for other platforms interested in 002 resin-based coatings</i>	<i>Invite representatives from interested WS SPOs to technical interchange meetings</i>	Versatility*

N/A	<i>Prove to be as durable or more durable than FP 60</i>	<i>Visually assess 002 resin (in the form of FP 212) during puffer box testing</i>	Durability
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*Versatility was achieved in the form of additional application of 002 resin besides FP 60-2 for the WS of interest

As Table 19 shows, the only deviation from the expected performance criteria was that durability was added as a qualitative performance criterion. During puffer box testing of FP 212, it was discovered that the 002 resin was much more durable than the 001 resin. Since the implications of this discovery were relevant for the WS interested in FP 60-2, durability was added as a criterion to be evaluated when comparing the performance of FP 60-2 to FP 60.

3.3 DATA EVALUATION

The 51 percent reduction in VOC content of FP 60-2 relative to FP 60 (213 g/L vs. 432 g/L) should result in significant life-cycle reductions in VOC and Hazardous Air Pollutant (HAP) emissions for the WS of interest. Table 20 shows expected life-cycle reductions in VOC and HAP emissions for the WS of interest by replacing FP 60 with FP 60-2.

Table 20. Expected VOC and HAP Life-Cycle Reductions for the FP 60-2-Targeted Weapon System of Interest

Pollutant	Emissions Reduction (lbs.)
VOC	386,840
HAP	447,625

Results from the FP 60-2 lab-scale application study were encouraging. They showed that FP 60-2 has acceptable application properties under a wide range of temperature and humidity conditions and indicated that FP 60-2 application properties are positively impacted when the temperature and humidity are increased. FP 60-2 airflow testing results showed that induced flaws in FP 60-2 do not propagate when acted upon by airflow and that the failure mode of FP 60-2 in high airflow conditions is acceptable. The extensive material properties testing that FP 60-2 went through led LM Aero and WS SPO engineers to conclude that FP 60-2 is qualified for the WS of interest. FP 60-2 showed exceptional application properties during the full-scale application study results. The fact that full-scale equipment and structures were used during the full-scale application study allows the results to be credible for what should occur during production and PDM operations. Finally, the 002 resin durability was an unexpected benefit of FP 60-2 relative to FP 60.

3.4 TECHNOLOGY COMPARISON

Overall, FP 60-2 performed better than expected and showed significant environmental and application improvements relative to FP 60. The exceptional performance of FP 60-2, combined with the fact that it is a drop-in replacement for FP 60 and that it does not pose increased risk to worker health, makes FP 60-2 a viable replacement for FP 60.

With a 51 percent decrease in VOC levels, FP 60-2 should perform better than FP 60 from an environmental stand-point. On a per aircraft basis, VOC emissions at production facilities should decrease when FP 60-2 replaces FP 60, which will improve work-place safety and decrease

regulatory burdens. From a production stand-point, FP 60-2 should decrease overall application time and cure time relative to FP 60. As a result, labor hours for material application and production flow times per unit should decrease. The increased durability of FP 60-2 compared to FP 60 in maritime environments should prove to result in substantial environmental and economic benefits over the life-cycle of the WS of interest. Repairs resulting from FP 60 degradation in maritime environments would result in aircraft downtime, material purchase/usage, labor hours, and VOC emissions to make PDM-level repairs. Implementation of FP 60-2 will significantly decrease the frequency and extent of aircraft repairs and all associated costs over the WS lifetime.

Additionally, as a result of this program, a few other 002 resin-based materials besides FP 60-2 have been qualified and transitioned to the WS of interest to replace baseline coatings other than FP 60 that are formulated with the 001 resin and that cover a significant portion of the aircraft. The testing of the additional 002 resin-based coatings was performed under a separate Air Force program that ran parallel to this program. It was outside the scope of this program to evaluate any coating other than FP 60-2 since it was not known until near the end of this program that the 002 resin would revolutionize the coating stack-up on the WS of interest. Therefore, the environmental and economic benefits resulting from this program as summarized in this report are extremely conservative. The benefits to the WS as a result of this program are expected to be orders of magnitude higher than the level of benefits summarized in this report due mainly to the increased durability of the 002 resin in maritime environments compared to the durability of the 001 resin.

As mentioned in Section 2.4 *Advantages and Limitations of the Technology*, there are two other technologies in addition to FP 60-2 that are being tested as alternatives to FP 60, a mold-in-place coating to replace a certain portion of FP 60 application during production processes and a UV cure coating mainly as a repair material for FP 60. Since these technologies have not completed all qualification testing, a full comparison to FP 60-2 is not possible. However, due to the special application methods of the mold-in-place and UV cure technologies, they would not be drop-in replacements for FP 60. Additionally, these alternatives may not have the same durability benefits relative to FP 60 that FP 60-2 has in maritime environments, which may not make these two other alternative technologies as attractive as FP 60-2 from the stand-point of LCC reductions relative to FP 60. Finally, FP 60-2 will replace FP 60 in its entirety during production processes at AFP 42, Palmdale, CA and AFP 4, Ft. Worth, TX, while the other two potential alternatives are being evaluated to replace only certain portions of FP 60 during production processes or when repairs are required.

4.0 COST ASSESSMENT

4.1 COST REPORTING

The cost assessment completed for this program follows the general format of the Environmental Cost Analysis Methodology (ECAM) that was developed by the National Defense Center for Environmental Excellence (NDCEE). A Level II ECAM analysis was performed on the technology demonstrated during this program. During puffer box testing and the full-scale application study, direct comparisons of 002 resin and 001 resin and of FP 60-2 and FP 60, respectively, were completed to evaluate properties that impact cost and performance and that therefore impact an ECAM. Puffer box testing closely mimics the temperatures, pressures, and exposures that a material experiences on an aircraft operating continuously in a maritime environment. This conclusion is based on field reports, including pictures, of 001 resin that has been applied to aircraft operating continuously in maritime environments. The field reports have proven the high degree of correlation of puffer box test results with the 001 resin degradation that occurs on actual aircraft. In order to quantify the benefits of the increased durability of the 002 resin in maritime environments, puffer box test results were used to estimate the degree and frequency of the degradation that would have occurred in 001 resin had it been applied to the WS of interest.

In order to compare application properties of FP 60-2 and FP 60, a full-scale application study was performed. The results from this study are highly accurate at determining what the application benefits of FP 60-2 will be compared to FP 60 during actual production implementation of FP 60-2 since this study was performed using full-scale spray equipment and a full-scale engineering prototype. The full-scale application study results were used to estimate the labor hour and flow time reductions that should result by transitioning FP 60-2. Relevant personnel at the production facilities where FP 60-2 will be transitioned were consulted to determine if and to what extent the Operations and Maintenance Costs, Indirect Environmental Activity Costs, and Other Costs would change if FP 60 was replaced with FP 60-2.

Tables 21 and 22 below summarize the Direct Environmental Activity Process Costs and Indirect Environmental Activity Costs for FP 60 and FP 60-2. Only those costs that differ between FP 60 and FP 60-2 were quantified. This assessment utilizes a basis founded on *per weapon system* costs for the purpose of cost reporting.

Table 21. ECAM Cost Reporting Table for Baseline Material (FP 60)

Direct Environmental Activity Process Costs				Indirect Environmental Activity Costs		Other Costs	
Start-Up		Operations & Maintenance					
Activity	Unit \$	Activity	Unit \$	Activity	Unit \$	Activity	Unit \$
Facility preparation, mobilization	NC	Labor for setup, application, cleaning, and repairs	\$32,000	Compliance audits	NC	NOT WITHIN THE SCOPE OF THIS PROGRAM	
Equipment Design	NC	Labor to manage hazardous waste	NC	Document Maintenance	NC		
Equipment purchase and installation	\$5,300	Utilities	NC	Envr. Mmgt. Plan development & maintenance	NC		
Training of operators	NC	Mgmt/Treatment of by-products	NC	Reporting requirements	NC		
		Hazardous waste disposal fees	NC	Test/analyze waste streams	NC		
		OEM & Depot Repair Coating Materials	\$26,000	Medical exams (including loss of productive labor)	NC		
		Process chemicals, Nutrients	NC	Waste transportation (on and off-site)	NC		
		Consumables and supplies	NC	OSHA/EHS training	NC		
		Equipment maintenance	NC				
		Training of operators	NC				
Totals Per Unit	\$5,300		\$58,000		NC		

No Change (NC) relative to FP 60-2 (costs held constant)

Table 22. ECAM Cost Reporting Table for FP 60-2

Direct Environmental Activity Process Costs				Indirect Environmental Activity Costs		Other Costs	
Start-Up		Operations & Maintenance					
Activity	Unit \$	Activity	Unit \$	Activity	Unit \$	Activity	Unit \$
Facility preparation, mobilization	NC	Labor for setup, application, cleaning, and repairs	\$4,100	Compliance audits	NC	NOT WITHIN THE SCOPE OF THIS PROGRAM	
Equipment Design	NC	Labor to manage hazardous waste	NC	Document Maintenance	NC		
Equipment purchase and installation	\$4,000	Utilities	NC	Envr. Mmgt. Plan development & maintenance	NC		
Training of operators	NC	Mgmt/Treatment of by-products	NC	Reporting requirements	NC		
		Hazardous waste disposal fees	NC	Test/analyze waste streams	NC		
		OEM & Depot Repair Coating Materials	\$15,400	Medical exams (including loss of productive labor)	NC		
		Process chemicals, Nutrients	NC	Waste transportation (on and off-site)	NC		
		Consumables and supplies	NC	OSHA/EHS training	NC		
		Equipment maintenance	NC				
		Training of operators	NC				
Totals Per Unit	\$4,000		\$19,500		NC		

No Change (NC) relative to FP 60 (costs held constant)

Tables 21 and 22 show that Start-Up Costs for FP 60-2 will be less than Start-Up costs for FP 60 due to decreased Equipment Purchase and Installation costs on a per unit basis if FP 60-2 is transitioned. The improved application properties of FP 60-2 will eliminate one spray booth that Northrop had planned to build to meet production goals. When this cost avoidance is spread out over the expected total number of aircraft to be produced, the result will be an estimated Equipment Purchase and Installation cost avoidance of \$1,300 per aircraft (the difference between \$5,300 for FP 60 and \$4,000 for FP 60-2).

As Tables 21 and 22 show, the most significant economic benefits of FP 60-2 will be the reduction in labor hours and flow times for production processes and the reduction in the frequency and extent of repairs, which will reduce downtime, labor costs, and material costs associated with repairs. Estimated Operations and Maintenance (O&M) costs on a per aircraft basis for FP 60 are \$58,000 and for FP 60-2 are \$19,500 for a reduction in total per unit costs of \$38,500.

Tables 21 and 22 indicate that the transition to FP 60-2 will have no impact on Indirect Environmental Activity Costs. The 51 percent reduction in VOC content of FP 60-2 relative to FP 60 (213 g/L vs. 432 g/L) will result in significant life-cycle reductions in VOC and HAP emissions. It is estimated that life-cycle VOC and HAP emissions of the WS of interest will be reduced by 386,840 pounds and 447,625 pounds, respectively, by replacing FP 60 with FP 60-2 in production and PDM operations. However, according to the facilities personnel who were consulted during this project who are located at facilities where FP 60-2 will be transitioned, the decrease in VOC and HAP reductions will most likely have no impact on Indirect Environmental Activity Costs.

The demonstration of FP 60-2 was funded jointly by AFRL/MLSC, ASC/ENVV, and ESTCP at a total cost of approximately \$1.37 million, with ESTCP contributing approximately \$920K. In-kind support from LM Aero and Northrop is not included in the \$1.37 million. The result of this investment was a fully-qualified, drop-in alternative for FP 60. As such, there will be no additional operational costs to implement FP 60-2.

4.2 COST ANALYSIS

In order to evaluate the cost performance of this program and the impacts of FP 60-2 transition, the series of negative cash flows that occurred to execute this program and the series of positive cash flows that are expected to occur once FP 60-2 is implemented are evaluated. Tables 23 and 24 report the negative cash flows (costs) that resulted from the cost of the FP 60-2 demonstration and the positive cash flows [expected annual cost savings (benefits)] once FP 60-2 is implemented, the present values of the costs and benefits, and the difference between the present values of the benefits and costs, which is the Net Present Value (NPV) of the series of negative and positive cash flows. Table 23 reports these financial metrics on a DoD-wide basis that includes costs contributed by AFRL/MLSC, ASC/ENVV, and ESTCP. Table 24 reports these financial metrics on an ESTCP basis that includes costs contributed by ESTCP only. The positive cash flows (expected annual benefits) reported in Tables 23 and 24 are the same since they both reflect the benefits that should occur once FP 60-2 replaces FP 60. The only difference between Tables 23 and 24 is the series of negative cash flows (costs) that occurred as the funding for the FP 60-2 demonstration was exhausted during the execution of this program. The negative cash flows in Table 23 represent the annual funding contributions by AFRL/MLSC, ASC/ENVV, and ESTCP combined (a total of approximately \$1.37 million) for the execution of this program. The negative cash flows in Table 24 represent the annual funding contributions by ESTCP only (a total of approximately \$920K) for the execution of this program.

Table 23. DoD-Wide Life-Cycle Cost Savings for FP 60-2 Implementation

Fiscal Year	2003	2004	2005	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Acct. Year	-4	-3	-2	0	1	2	3	4	5	6	7	8	9	10	11
Benefits				\$12K	\$4117K*	\$23K	\$35K	\$40K	\$87K	\$173K	\$1156K	\$1445K	\$1445K	\$1445K	\$1445K
Costs	\$419K	\$616K	\$336K												

Fiscal Year	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
Acct. Year	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Benefits	\$1445K	\$1504K	\$1504K	\$1563K	\$1135K	\$294K	\$883K	\$2944K	\$4416K	\$4416K	\$4416K	\$4416K	\$4416K	\$4475K	\$4475K
Costs															

Fiscal Year	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2057
Acct. Year	27	28	29	30	31	32	33	34	35	36	37	38	39	40	50
Benefits	\$4534K	\$353K	\$294K	\$883K	\$2944K	\$4416K	\$4416K	\$4416K	\$4416K	\$4416K	\$4416K	\$4416K	\$4416K	\$236K	
Costs															

Present Benefits = \$48,823,000 Present Costs = \$1,501,000 NPV = \$47,322,000

*Includes a significant capital cost avoidance by eliminating one spray booth

Table 24. ESTCP Life-Cycle Cost Savings for FP 60-2 Implementation

Fiscal Year	2003	2004	2005	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Acct. Year	-4	-3	-2	0	1	2	3	4	5	6	7	8	9	10	11
Benefits				\$12K	\$4117K*	\$23K	\$35K	\$40K	\$87K	\$173K	\$1156K	\$1445K	\$1445K	\$1445K	\$1445K
Costs	\$191K	\$441K	\$288K												

Fiscal Year	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
Acct. Year	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Benefits	\$1445K	\$1504K	\$1504K	\$1563K	\$1135K	\$294K	\$883K	\$2944K	\$4416K	\$4416K	\$4416K	\$4416K	\$4416K	\$4475K	\$4475K
Costs															

Fiscal Year	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2057
Acct. Year	27	28	29	30	31	32	33	34	35	36	37	38	39	40	50
Benefits	\$4534K	\$353K	\$294K	\$883K	\$2944K	\$4416K	\$4416K	\$4416K	\$4416K	\$4416K	\$4416K	\$4416K	\$4416K	\$236K	
Costs															

Present Benefits = \$48,823,000 Present Costs = \$1,002,000 NPV = \$47,821,000

*Includes a significant capital cost avoidance by eliminating one spray booth

Since FP 60-2 is a drop-in replacement for FP 60, there will be no additional out-year operational costs by replacing FP 60 with FP 60-2. As a result, the only negative cash flows that occur are due to the costs of the FP 60-2 demonstration (the costs of executing this ESTCP program). Once FP 60-2 is implemented, positive cash flows will result as the expected economic savings of FP 60-2 begin to be realized. The present values of the negative cash flows (costs) and positive cash flows (benefits) were determined by using an extrapolated Office of Management and Budget (OMB) discount rate of 3.0 percent based on the selected ECAM evaluation period of 50 years. The 50-year evaluation period was selected to fully account for the environmental and economic benefits that will be realized by using FP 60-2 at production and PDM locations during the lifetime of the WS of interest. PDM-level repairs would have been required to be made to FP 60 applied to aircraft operating primarily in maritime environments up to two times during the WS life cycle (once approximately half way through the life cycle and once near the end of the life cycle). In order to account for the aircraft that are currently in production and those that will not be produced for several years, and then to consider the entire life cycle span of each aircraft in order to account for the cost savings by avoiding two PDM-level repairs by replacing FP 60 with FP 60-2, a 50-year evaluation period was required. The 3.0 percent discount rate accounted for the time value of money and permitted the estimation of life-cycle cost savings for government and Original Equipment Manufacturer (OEM) implementation of FP 60-2.

As reported in Tables 23 and 24, the present values of the benefits are significantly higher than the present values of the costs, resulting in total NPV of \$47.3 million and \$47.8 million for DoD as a whole and for ESTCP, respectively. Using the annual cost savings reported in Tables 23 and 24, the simple payback period and Internal Rate of Return (IRR) are calculated. The payback periods for the investments made in this program by DoD as a whole and by ESTCP are both less than one year. The estimated IRRs based on DoD-wide and ESTCP contributions are 36.9 percent and 49.5 percent, respectively. Table 25 summarizes the relevant expected financial metrics on a DoD-wide basis and for ESTCP, based on the benefits of FP 60-2 relative to FP 60.

Table 25. Summary of Expected Financial Metrics Resulting from Implementation of FP 60-2

Financial Metric	DoD-Wide Contributions	ESTCP Contributions Only
NPV	\$47.3 million	\$47.8 million
Payback Period	<1 year	<1 year
IRR	36.9%	49.5%

The cost savings and financial metrics reported in Table 25 are extremely conservative since, as a result of this program, LM Aero and SPO engineers decided to transition other 002 resin-based materials besides FP 60-2 to the WS of interest to replace baseline materials other than FP 60 that were formulated with the 001 resin and that covered a significant portion of the aircraft. Consequently, the results of this program are expected to increase the level of environmental and economic savings for the WS of interest by orders of magnitude relative to those summarized in this report due to the increased durability of the 002 resin in maritime environments compared to the durability of the 001 resin in maritime environments.

The major cost drivers associated with FP 60 are: (1) low build rate, (2) the length of material cure times, and (3) expected degradation in maritime environments. These cost drivers lead to relatively high labor and material application costs, lengthy flow times, and significant costs associated with repairs. In turn, the relatively high process flow time negatively impacts OEM and PDM weapon system delivery schedules and can impact overall mission readiness. FP 60-2 has significant advantages relative to FP 60 in all of the stated cost driver categories. As such, the investment in demonstrating and validating FP 60-2 will be extremely rewarding. The drop-in replacement status of FP 60-2, combined with significant annual and LCC reductions, will lead to excellent financial metrics for DoD as a whole and ESTCP.

Table 26 provides the results of a sensitivity analysis performed on the major cost drivers for FP 60-2.

Table 26. FP 60-2 Sensitivity Analyses of Cost Drivers

Sensitivity Analysis:		
Overall DoD NPV	Simulation Mean =	\$47,313,122.44
	Simulation Sigma =	\$8,649,404.22
ESTCP NPV	Simulation Mean =	\$47,811,962.03
	Simulation Sigma =	\$8,649,404.22
	Trials =	250
95% Confidence Interval:		
Overall DoD NPV	Lower Bound =	\$46,240,950.88
	Upper Bound =	\$48,385,293.99
ESTCP NPV	Lower Bound =	\$46,739,790.48
	Upper Bound =	\$48,884,133.58

Based on a simulation size of 250 trials, the FP 60-2 95 percent Confidence Interval (CI) for DoD-wide NPV equals a gain of between \$46.2 million and \$48.4 million. Similarly the FP 60-2 95 percent CI for ESTCP NPV equates to a gain of between \$46.7 million and \$48.9 million over the WS life-cycle.

4.3 COST COMPARISON

Overall, FP 60-2 demonstrates highly positive LCC savings due to its application and durability benefits relative to FP 60 and due to its early implementation into the WS projected life-cycle. As such, FP 60-2 is an extremely attractive alternative to FP 60. Cost savings of FP 60-2 relative to the mold-in-place and UV cure technologies, which are currently being tested, is not possible at this time.

While the significant environmental benefits of this program will most likely not result in economic savings, they are still considered and quantified for the positive impacts they will have on the environment and human health. The release of VOC and HAP emissions into the Earth's atmosphere impacts air quality and increases the risk of health problems. VOCs have been shown to contribute to the formation of ground-level ozone, which is a pollutant and can lead to severe respiratory problems and can damage crops and vegetation. HAPs are known or suspected carcinogens. Through the use of FP 60-2, approximately 386,840 pounds of VOC emissions and 447,625 pounds of HAP emissions will be eliminated from production and PDM operations during the life-cycle of the WS of interest.

5.0 PERFORMANCE ANALYSIS – OVERALL ESTCP PROJECT WP-0303

As mentioned in Section 1.1 *Scope of ESTCP Project WP-0303*, this ESTCP project involved the testing and demonstration of two low VOC, rapid deposition, quick cure aerospace coatings, FP 60-2 and FP 212, in addition to the baseline coatings that will be replaced by FP 60-2 and FP 212. The financial metrics reported in Sections 5.1 – 5.3 of this report took into consideration the costs of testing and demonstrating FP 60-2 and the expected annual benefits of replacing FP 60 with FP 60-2. In order to provide an evaluation of environmental performance and cost effectiveness of the overall ESTCP Project WP-0303, the costs and benefits associated with testing and demonstrating FP 212 and replacing the baseline material (the baseline material of the FP 212-targeted WS) with FP 212 need to be combined with those of FP 60-2 reported in this report.

5.1 ENVIRONMENTAL PERFORMANCE ANALYSIS – OVERALL ESTCP PROJECT WP-0303

Table 27 reports the expected VOC and HAP emissions reductions by replacing the baseline material of the FP 212-targeted WS of interest with FP 212. The justification for the information reported in Table 27 is detailed in the ESTCP Cost and Performance Report for FP 212, which is available from ESTCP.

Table 27. Expected VOC and HAP Life-Cycle Reductions for the FP 212-Targeted Weapon System of Interest

Pollutant	Emissions Reduction (lbs.)
VOC	11,131
HAP	12,938

Table 27 reports that there are expected to be VOC and HAP emissions reductions for the FP 212-targeted WS of interest if FP 212 replaces the baseline material of the FP 212-targeted WS of interest. The emissions reductions reported in Table 27 are not nearly as significant as those that will be realized by replacing FP 60 with FP 60-2, as reported in Table 20, but they increase the expected emissions reductions of the overall ESTCP Project WP-0303. However, as specified in the FP 212 Cost and Performance Report, which is available from ESTCP, other 002 resin-based materials besides FP 212 will replace other 001 resin-based materials besides the baseline material of the FP 212-targeted WS as a result of this ESTCP project. If the other 002 resin-based materials besides FP 212 have environmental advantages relative to the 001 resin-based materials that they will replace, then the environmental benefits for the FP 212-targeted WS of interest will be greater than those reported in Table 27.

Table 28 reports the expected emissions reductions for the overall ESTCP Project WP-0303 by combining the reductions in Table 27 with those of FP 60-2 in Table 20.

Table 28. Expected VOC and HAP Life-Cycle Reductions for the FP 60-2 and FP 212-Targeted Weapon Systems of Interest

Pollutant	Emissions Reduction (lbs.)
VOC	397,971
HAP	460,590

As Table 28 reports, the expected emissions reductions for the overall ESTCP project are significant. The replacement of FP 60 by FP 60-2 accounts for the majority of the expected emissions reductions, but replacing the baseline material of the FP 212-targeted WS of interest with FP 212 adds to the expected emissions reductions. However, the emissions reductions estimates reported in Table 28 are extremely conservative since, as a result of this program, other 002 resin-based materials besides FP 60-2 will be transitioned to the WS of interest to replace baseline materials other than FP 60 that were formulated with the 001 resin and that cover a significant portion of the aircraft. As the FP 212 Cost and Performance Report indicates, the same is true for 002 resin-based materials and the FP 212-targeted WS of interest. The increased durability of the 002 resin in maritime environments relative to the durability of the 001 resin in maritime environments will lead to fewer repairs, which will decrease the level of VOC and HAP emissions from applying materials during repair processes.

Additionally, as a result of this ESTCP project, LM Aero and certain SPO personnel are considering the transition of 002 resin-based materials to a WS other than the FP 60-2-targeted WS and other than the FP 212-targeted WS. This additional WS is currently coated primarily with 001 resin-based materials and will benefit greatly from the increased durability of the 002 resin in maritime environments relative to the durability of the 001 resin in maritime environments since many of the aircraft of this additional WS operate continuously in maritime environments. Therefore, as a result of this ESTCP project, at least two (and possibly three) DoD WS platforms will benefit greatly, and the environmental benefits for DoD should be orders of magnitude higher than those summarized in this report.

5.2 ECONOMIC PERFORMANCE ANALYSIS – OVERALL ESTCP PROJECT WP-0303

Table 29 summarizes the relevant expected financial metrics on a DoD-wide basis and for ESTCP only, based on the benefits of FP 212 relative to the baseline material of the FP 212-targeted WS of interest. The justification for the information reported in Table 29 is detailed in the ESTCP Cost and Performance Report for FP 212, which is available from ESTCP.

Table 29. Summary of Expected Financial Metrics Resulting from Implementation of FP 212

Financial Metric	DoD-Wide Contributions	ESTCP Contributions Only
NPV	-\$401K	-\$326K
Payback Period	N/A*	N/A*
IRR	-18.6%	-17.0%

*The total expected positive cash flows (estimated cumulative annual cost savings) are lower than the total negative cash flows (cost of the FP 212 testing and demonstration)

As Table 29 shows, the NPV on a DoD-Wide basis and for ESTCP are both negative since the present value of the costs associated with testing and demonstration of FP 212 are greater than the present value of the expected benefits of replacing the baseline material with FP 212. As a result, the costs of testing and demonstrating FP 212 will not be “paid back” and the IRRs for the DoD-wide contributions and ESTCP-only contributions are negative. However, as specified in the FP 212 Cost and Performance Report, which is available from ESTCP, other 002 resin-based materials besides FP 212 will replace other 001 resin-based materials besides the baseline material of the FP 212-targeted WS as a result of this ESTCP project. If the other 002 resin-based materials besides FP 212 have application advantages relative to the 001 resin-based materials that they will replace, then the financial metrics for the FP 212-targeted WS of interest will be better than those reported in Table 29.

Table 30 summarizes the relevant expected financial metrics on a DoD-wide basis and for ESTCP for the overall ESTCP Project WP-0303.

Table 30. Summary of Expected Financial Metrics Resulting from Implementation of FP 60-2 and FP 212

Financial Metric	DoD-Wide Contributions	ESTCP Contributions Only
NPV	\$46.9 million	\$47.5 million
Payback Period	<1 year	<1 year
IRR	30.9%	39.7%

As reported in Table 29, even though the financial metrics for the FP 212 portion of ESTCP Project WP-0303 are negative, the overall financial metrics for ESTCP Project WP-0303 are extremely attractive, as Table 30 reports, due to the substantial economic benefits that are expected to result by replacing FP 60 with FP 60-2, as reported in Table 25. However, these financial metric estimates are extremely conservative since, as a result of this program, other 002 resin-based materials besides FP 60-2 will be transitioned to the FP 60-2-targeted WS of interest to replace baseline materials other than FP 60 that are formulated with the 001 resin and that cover a significant portion of the aircraft. As the FP 212 Cost and Performance Report indicates, the same is true for 002 resin-based materials and the FP 212-targeted WS of interest.

Additionally, as a result of this ESTCP project, LM Aero and certain SPO personnel are considering the transition of 002 resin-based materials to a WS other than the FP 60-2-targeted WS and other than the FP 212-targeted WS. This additional WS is currently coated primarily with 001 resin-based materials and will benefit greatly from the increased durability of the 002 resin in maritime environments relative to the durability of the 001 resin in maritime environments since many of the aircraft of this additional WS operate continuously in maritime environments. Therefore, as a result of this ESTCP project, at least two (and possibly three) DoD WS platforms will benefit greatly, and the economic benefits for DoD should be orders of magnitude higher than those summarized in this report.

5.3 OVERALL ANALYSIS OF ESTCP PROJECT WP-0303

The two materials demonstrated and validated during this project, FP 212 and FP 60-2, have lower VOC contents and superior application properties than the materials they will replace. These advantages are expected to result in environmental and economic benefits for the facilities that transition these materials. The durabilities of FP 212 and FP 60-2 in maritime environments were demonstrated to be far superior to the durabilities in maritime environments of the materials that they will replace due to the superior durability of the 002 resin in maritime environments compared to the durability of the 001 resin in maritime environments. It is anticipated that transitioning to 002 resin-based materials will allow aircraft that operate continuously in maritime environments to avoid material degradation that would require PDM-level repairs.

The results of this ESTCP project have revolutionized the material stack-ups of two WS platforms of interest, and a third WS is strongly evaluating the results of this project. As a result of this ESTCP project, the material stack-ups have shifted from 001 resin-based materials to 002 resin-based materials, due mainly to the superior durability of the 002 resin in maritime environments compared to the durability of the 001 resin in maritime environments. The increased durability of the 002 resin relative to the 001 resin will have far-reaching beneficial impacts to aircraft that operate continuously in maritime environments. Life-cycle VOC and HAP emissions reductions will significantly decrease the life-cycle environmental foot-print of the two WS platforms of interest. The cost reductions to be realized over the life-cycle of the two WS platforms of interest have resulted in financial metrics for this ESTCP project that are highly favorable. Additionally, LM Aero is considering the transition of 002 resin-based materials to replace 001 resin-based materials on a WS platform other than the two targeted during this project. The environmental and economic benefits that DoD should realize as a result of this ESTCP project are expected to be orders of magnitude higher than those reported in this Cost and Performance Report since it was outside the scope of this project to evaluate the benefits of all of the 002 resin-based materials that will be transitioned to the two WS platforms of interest and possibly to a third WS of interest.

6.0 IMPLEMENTATION ISSUES

6.1 COST OBSERVATIONS

The initial difficulties with the roller peel testing caused minor escalations in the estimated cost for demonstrating FP 60-2. These kinds of difficulties are common when evaluating new materials. Lessons learned from this program should result in avoidance of the difficulties experienced with roller peel testing should cohesion and adhesion testing be required for future programs.

In general, aerospace coating vendors provide a tiered pricing scale for coating material purchases. Tiered pricing is a direct reflection of the economies of scale achieved by manufacturing larger product batches. Therefore, a large volume procurement of FP 60-2 has the potential to reduce the material purchase cost element of FP 60-2.

6.2 PERFORMANCE OBSERVATIONS

FP 60-2 showed some differences to FP 60 with respect to physical and mechanical properties. In general, FP 60-2 has lower viscosity and hardness properties than FP 60 at common temperatures. Lower hardness properties lead to lower tensile strength at common temperatures compared to FP 60. These differences in physical and mechanical properties did not cause great concern with LM Aero and SPO engineers and will not prevent FP 60-2 from being transitioned.

Difficulties experienced during roller peel testing caused a slight deviation from the initial test plan. After several iterations of roller peel testing resulted in inconclusive results (despite lowering the test temperature and trying several different test specimen preparation methods), it was decided to perform T-peel testing to evaluate the cohesive properties of FP 60-2. The T-peel test results were conclusive and acceptable.

Relative to FP 60, FP 60-2 demonstrated environmental and cost savings. The only primary performance criteria established for FP 60-2 that were not fully achieved were the reduction in application time and material usage. The goal for reduction in application time was at least 75 percent, but testing showed that application time was reduced by only 33 percent. The goal for reduction in material usage was at least 20 percent, but testing showed that material usage was reduced by only 18 percent. These results will not delay or halt the planned implementation of FP 60-2 since significant LCC savings will be realized by implementing FP 60-2.

6.3 SCALE-UP

The transition of FP 60-2 to full-scale production processes should run smoothly from a procedural standpoint. Transition risk was minimized during this program as FP 60-2 was designed as a drop-in replacement for FP 60 and since FP 60-2 was evaluated during certain tasks using manual full-scale spray equipment and full-scale engineering prototypes. No further spray trials will need to be performed at AFP 4, where FP 60-2 will be applied during production processes with the same full-scale manual spray equipment that was used during the full-scale application study during this program. FP 60-2 will be applied At AFP 42 during production processes using a robotic spray system. Prior to implementation, Northrop will conduct spray optimization testing with FP 60-2

using the robotic spray system. Since FP 60-2 has improved application properties relative to FP 60, Northrop may have to modify the path planning for the robotic spray system. There are expected to be no major difficulties with spraying FP 60-2 or with modifying the robotic spray system to optimize FP 60-2 application performance. Northrop will use the results of the lab-scale and full-scale application studies performed during this program to make the process of modifying the robotic path planning extremely efficient. The robotic spray optimization is being funded by the SPO of the WS of interest.

6.4 OTHER SIGNIFICANT OBSERVATIONS

Major factors that could present roadblocks to effective implementation of FP 60-2 have been adequately explored and addressed. Environmentally-advantaged coatings have strong support from the appropriate OEMs, and end user buy-in has already been achieved. Also, significant reductions in the VOC content of FP 60-2 have been demonstrated. Therefore, environmental compliance is not expected to hinder technology implementation in any way.

6.5 LESSONS LEARNED

Other programs interested in implementing FP 60-2 will benefit greatly from the lab-scale and full-scale application study data generated during this program. This data will provide application guidance in terms of maximum build rate, ideal time between passes, cure time, and how environmental conditions can affect application properties.

6.6 END-USER/ORIGINAL EQUIPMENT MANUFACTURER ISSUES

The prime contractor and subcontractor for the WS of interest, LM Aero and Northrop, respectively, had significant involvement in this program. The lab-scale application study was performed by LM Aero and Northrop at the Northrop facility in El Segundo, CA, and the lab-scale qualification testing, airflow testing, and full-scale application study were performed by LM Aero at AFP 4, Ft. Worth, TX. The puffer box test was also performed by LM Aero at AFP 4. In attendance at the Technical Interchange Meetings (TIMs) for this program were the relevant LM Aero and Northrop engineers, as well as relevant SPO engineers for the WS of interest.

After all testing performed under this program was completed, the final Technical Interchange Meeting (TIM) for this program was held at the SAIC facility in Dayton, OH on 11 April 2007. In attendance at the meeting were the ASC/ENVV program manager, the relevant SPO representatives from both the Air Force and Navy (NAVAIR), the LM Aero manager for Materials and Processes, additional LM Aero engineers, and SAIC engineers. After a review of all test data generated during this program, the decision was made to begin production acceptance testing of FP 60-2. This decision indicates that the relevant LM Aero and SPO engineers feel that the physical, mechanical, and other properties of FP 60-2, as outlined in the relevant material specification, are acceptable and that FP 60-2 will be listed on the LM Aero QPL. For production acceptance testing, full-scale production batches of FP 60-2 will be ordered and sent to AFP 42, where Northrop will perform spray optimization evaluations. LM Aero will test a few kits (gallons) from each full-scale batch to evaluate variability in critical properties from batch to batch. The objective of production acceptance testing is to finalize preparations for FP 60-2 transition into production processes. Once production acceptance testing is completed, FP 60-2 will be

transitioned to production processes, assuming no major problems are encountered. It is highly unlikely that any major problems will be experienced during production acceptance testing since there were no major problems encountered during FP 60-2 testing at any previous point in this program. Production acceptance testing will be funded by the SPO of the WS of interest.

6.7 APPROACH TO REGULATORY COMPLIANCE AND ACCEPTANCE

Title V of the Clean Air Act (CAA) was the primary regulatory driver for this project. There was no involvement or interaction with regulators or governmental validation programs beyond that which was part of normal day-to-day operations at the Northrop, El Segundo, CA facility, AFP 42, Palmdale, CA and AFP 4, Ft. Worth, TX.

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